REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
28-02-2008	Final	01-03-2005 – 30-11-2007

4. TITLE AND SUBTITLE

Compliant Frame: A New Paradigm to Enable Reconfigurable Aircraft Structures

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-05-1-0165

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AERSP-GAL-0228

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Department of the Air Force
Air Force Office of Scientific Research
875 North Randolph Street
Arlington, VA 22203-1768

10. SPONSOR/MONITOR'S ACRONYM(S)

AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - distribution is unlimited

AFRL-SR-AR-TR-08-0164

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Reconfigurable ("morphing") aircraft offer the potential for efficient flight over a large range of airspeeds. The structural concept addressed herein is a tendon-actuated cellular compliant frame, with a flexible skin. 3-D cellular structures can perform well, but the need for active tendons to also carry passive lift loads limits their feasibility at larger scales. 2-D cellular structures can significantly change wing area and span, with lower actuation forces, and a system of parallel actuators is significantly lighter than a single actuator, especially at higher gross weights. Composite skins with cellular cores and flexible face sheets show promise for low-force actuation with reasonable lateral stiffness, while contact-aided cores offer additional benefits, including stress relief and increased lateral stiffness. Finally, while the potential benefits of morphing increase with aircraft gross weight, structural morphing capability decreases; this is accompanied by increasing structural and actuation weight fractions. This suggests that, for a given structural paradigm, there is a gross weight at which smooth morphing is most advantageous and practical. Continued research is needed to address the many challenges that remain before the promise of smoothly morphing aircraft can be realized.

15. SUBJECT TERMS

aircraft, morphing, reconfigurable geometry, compliant mechanism, topology optimization, genetic algorithm, variable span wing, scaling , flexible skin, cellular core, contact-aided mechanism

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			George A. Lesieutre
U	U	U	UU	23	19b. TELEPHONE NUMBER (Include area code) 814-863-0103

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

AFOSR Final Report

February 28, 2007

**COMPLIANT FRAME:
A NEW PARADIGM TO ENABLE
RECONFIGURABLE AIRCRAFT STRUCTURES**

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1. Background

Smooth shape reconfiguration or "morphing" of aircraft structures enables the contemplation of missions that involve segments requiring responsiveness (dash) and persistence (loiter) [1]. Important capabilities made possible by morphing include efficient flight over a broad range of flight speeds and effective high-rate maneuvering [2-7]. For efficient flight, the main needs are large changes in wing area (span and chord), along with sweep and thickness [7-11]. For flight control, the required capability involves rapid modifications of local camber and twist [12]. The development of a structural concept capable of changing shape smoothly while carrying loads is a challenge. Most of the approaches so far have used traditional methods like discrete rotating and sliding joints [13, 14].

In order to achieve a continuously morphing aircraft wing that eliminates hinged joints, numerous stringent design requirements must be met. The internal structure of the wing must be able to support aerodynamic loads, an actuation system must be able to work against these loads, and an adequate skin cover that can deform with the internal structure while remaining stiff under aerodynamic loads must be provided. The subject research focused on development of the internal wing structure and skin.

The research described in this report aimed to develop a structural concept capable of achieving continuous stable deformations over a large range of aircraft shapes. The basic concept underlying the approach is a *compliant cellular frame,* with *tendons* used as active elements. The members of the frame are connected through compliant joints such that only modest bending moments may be transmitted from one member to another, as in a truss structure. Actuation is achieved by pulling on one set of cables while controlling the release of another, so that the stability of the structure is maintained in any intermediate position. The tendon-actuated frame can be made to behave locally, and temporarily, as a (compliant) mechanism, by releasing appropriate cables. As a result, in the absence of aerodynamic forces, the structure can be morphed using relatively low forces.

In an alternate approach, cellular compliant mechanisms were employed to achieve the desired wing shape change. The design process involves an initial stage wherein an appropriate cell mechanism that can achieve the desired wing shape change is intuitively determined. Thereafter, design parameters such as cell wall thickness and length, and cell wall angle must be calculated such the desired wing shape change is achieved, and the resultant structure is stiff against aerodynamic loads. The placement of actuators is a design parameter that may be determined either intuitively or by using an optimization procedure. The cellular mechanism design is particularly useful in cases where two-dimensional wing morphing is desired, since the optimal topology in two-dimensional morphing can be easy to visualize. It has been used in this work for morphing of the TSCh wing from NextGen Aeronautics Inc.

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A 2-D concept was also developed. This concept utilizes a compliant-cellular-truss structure with the ability to change span, and consequently, the planform area and aspect ratio of the wing. The base structure consists of an arrangement of unit cells. These cells are distributed throughout the wing structure such that the structure is contained within a specified percentage of the chord, wing thickness, and span. Using cables, the structure can be actuated such that large changes, primarily in the direction of the span, are achieved. Reeling in the cables reduces the span of the structure, decreasing both the wetted area and aspect ratio of the wing. The morphing performance and structural weight of this concept was determined for a variety of different sized aircraft.

A skin system is required that can accommodate large shape changes while carrying and transferring aerodynamic loads. Desired properties of the skin are: (1) high strain capability; (2) low membrane stiffness, for reasonable actuation forces; (3) high bending stiffness, to prevent local deformation due to surface pressure and buckling of sections under compressive loading; and (4) high in-plane shear stiffness, for good wing torsional stiffness. The focus concept was a composite skin comprising high-strain capable, low-modulus face sheets (silicone/polymer) covering a cellular honeycomb core. The overall properties of the skin are largely governed by the core. The core itself can comprise single or multiple layers. A contact mechanism was also used to improve the global strain capability of the cellular structures.

2. Methods

This section briefly describes various tools that were developed as part of this research.

2.1 Compliant 3-D cell

A parallel genetic algorithm (GA) was developed for the design of 3-D unit cells using topology optimization. A fitness value is assigned to each of many candidate structural realizations. This fitness value is a measure of how well a structure meets the design requirements. The developed fitness function was formulated such that it includes the stiffness and stability of the structure under aerodynamic loads, as well as the morphing morphing performance under actuation. In the course of the global optimization, forces in the cables are optimized to obtain the best match between the deflection of the morphed structure and the desired configuration.

2.2 Compliant 2-D cell

A 2-D compliant cellular truss structure was designed for a morphing aircraft. 2-D designs were specifically considered in order to reduce actuation forces and structural weight relative to those of 3-D designs. Such structures can exhibit large changes in planform area. Wings with the maximum span or in the fully extended position are useful for efficient low speed flight, and with minimum span or in the fully contracted position, for efficient high speed flight. The actuation for expanding and contracting the wing span is achieved using cables. The analysis assumed that the cables are passive for the structural loads.

2.3 Flexible skin design

The morphing aircraft skin was addressed using two passive approaches. The focus was on composite skins comprising high-strain capable, low-modulus face sheets (silicone/polymer) covering a cellular honeycomb core. The overall properties of the skin, then, are largely governed by the core. The core itself can comprise single or multiple layers. In the first approach honeycomb and auxetic (negative Poisson's ratio) cells were considered, while in the second approach the honeycomb and auxetic cells were modified by adding a contact mechanism to improve the load-carrying and global strain capability of the skin. The size of cell was determined to suit the required morphing.

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3. Results and Discussion

This section summarizes the major results obtained using the described methods.

3.1 Compliant 3-D cell

Optimization of unit cell geometry using a Genetic Algorithm (GA) yielded a six-noded octahedral unit cell with diagonal tendon actuation (Figure 1). Details can be found in [15]. Depending on the aspect ratios of the cell, different effective strains can be obtained in various directions. In specific applications, such as the NASA HECS wing, initial cell geometry and orientation are determined by "strain matching" the cell deformation to the local morphing deformation required. The cell size is dictated by the available space, the morphing strain, and discretization errors in approximating a smooth desired wing-surface shape.
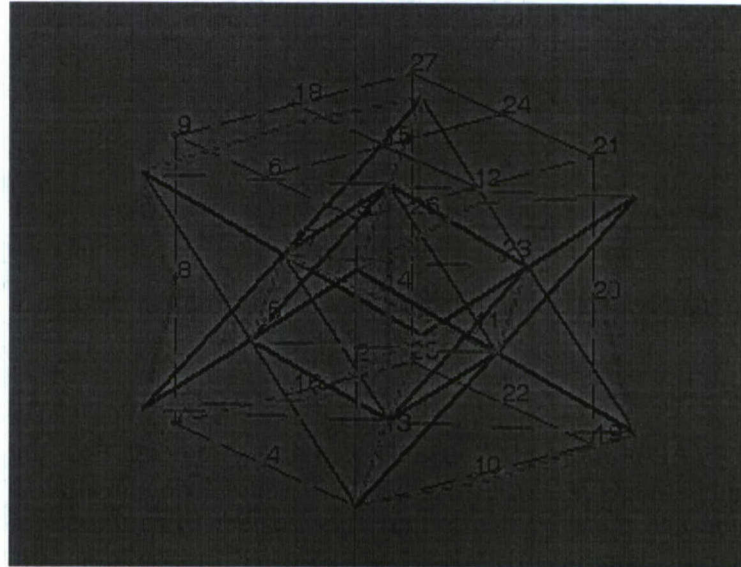

Figure 1: 3D unit cell geometry with uniform displacement

A finite element analysis was performed on a wing made of these unit cells and sized for a representative vehicle weighing 3000 lbs (1360 kg), with a load factor of ±4 and factor of safety of 1.5 (Figure 2). The weight of the wing structure (without skin and actuators) is comparable to that of conventional stiffened-skin construction, although its deflections are larger (Figure 3). Aeroelastic concerns of flutter and divergence can perhaps be addressed through the use of active control, as in the Active Aeroelastic Wing (AAW) program.
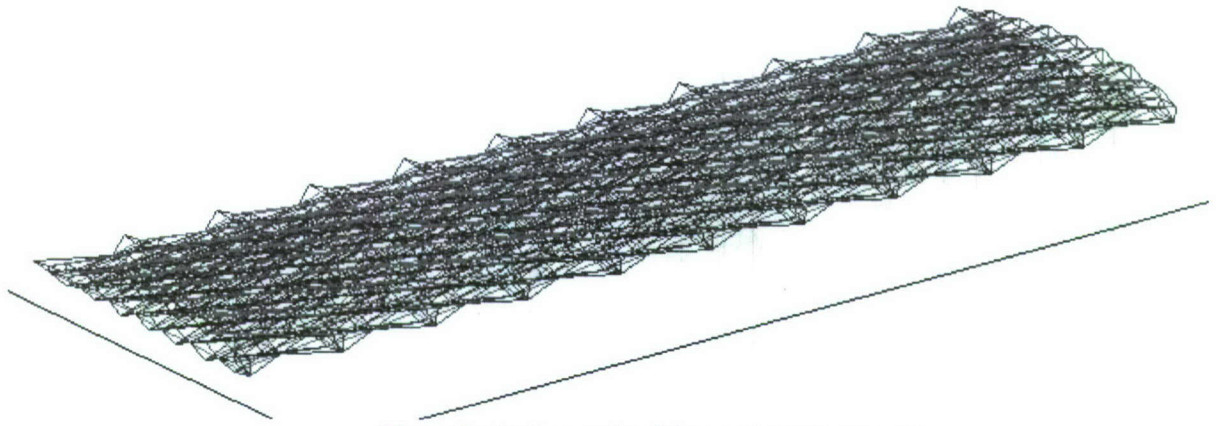
7

Figure 2: A wing made of the octahedral unit cells

New Proposed Truss Structure

Bay Cross-section

NASA HECS Wing

■ Cables
■ Struts
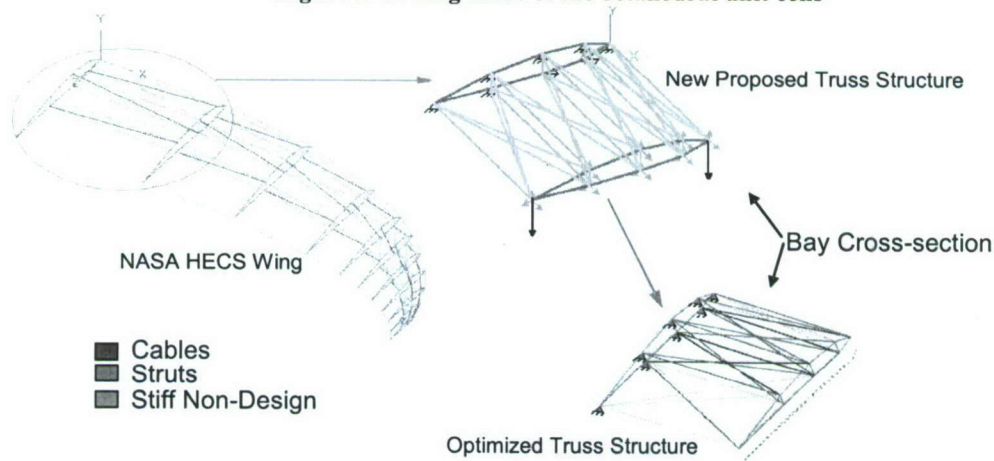■ Stiff Non-Design

Optimized Truss Structure

Figure 3: Ground structure for HECS wing

Nonlinear finite element analysis was used to address the large deformations of morphing structures. A discrete-continuous genetic algorithm was developed that optimizes the discrete elements in the truss structure (cable, truss, or void) and the continuous actuation applied to the cables. The NextGen TSCh Wing problem was considered as an example, in which large changes in sweep and span are desired. The wing morphing was formulated as prescribed deflection of n points along the outer section of a single bay. Since the designed wing must be simultaneously flexible under actuation forces and stiff under aerodynamic loads, the formulation uses two conflicting objectives: a_1 minimizes the squared error between desired and obtained deflections under actuation, while a_2 minimizes the squared error between deflection under air-loads and the original undeformed configuration. Essentially a_1 aims to maximize the deflection under actuation, or in other words, maximizes the flexibility of the structure. In turn a_2 minimizes the deflection under air loads, or tries to stiffen the structure. The stress constraint is imposed on all cables and struts to ensure that their stresses lie below the yield stress of their material (Cable – Stainless Steel 304 and Strut – Aluminum 7075 T6). In addition, a volume constraint is applied to the total cable and strut volume in order to limit the weight of struts and cables present in the topology solution, thereby preventing the presence of excess amount of cables or struts. A typical process showing the ground structure, the optimized truss structure for

the HECS wing is shown in Figure 3. The process is almost the same for other type of wing models.

$$a_1 = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_{DEFActAir,i} - x_{DES,i})^2 + (y_{DEFActAir,i} - y_{DES,i})^2 + (z_{DEFActAir,i} - z_{DES,i})^2}$$

$$a_2 = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_{DEFAir,i} - x_{ORIG,i})^2 + (y_{DEFAir,i} - y_{ORIG,i})^2 + (z_{DEFAir,i} - z_{ORIG,i})^2}$$

$$\sigma_i \leq \sigma_{Yield\,i}$$

$$V_{active} \leq \frac{x}{100}V_{total}$$

$$V_{passive} \leq \frac{y}{100}V_{total}$$

The following sections give a sample set of results based on the preceding algorithm and methodology. A more complete set of results is provided in [16].

3.1.1 HECS wing

The genetic algorithm was used to design a morphing wing structure for the root bay of NASA's HECS wing design.

(a) Un-morphed Configuration   (b) Morphed Configuration
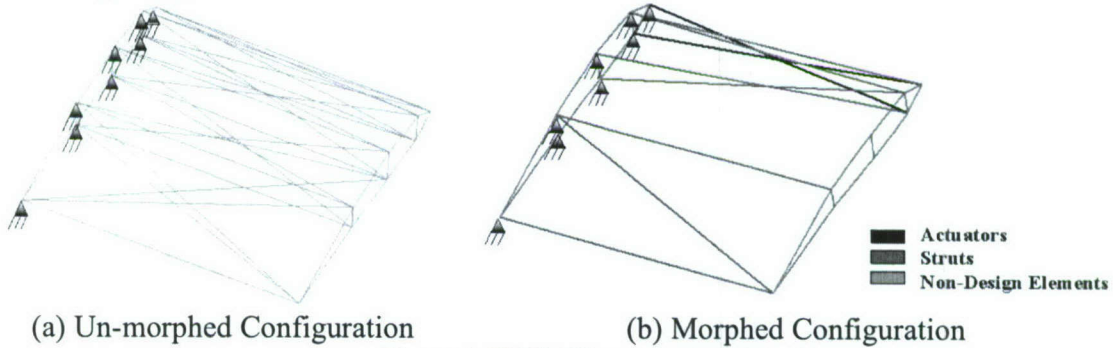
Figure 4: HECS Wing – Optimal Topology

Figure 3(a) gives the initial ground structure un-morphed configuration while Figure 3(b) gives the optimal topology for the HECS wing. The final bay topology consisted of 2 cables, 7 struts and 15 voids. The obtained leading edge nodal deflections and their desired values are given in Table 1 for the leading edge node of the first bay. The leading edge nodal deflection is found to closely match the desired value. The average amount of actuation force per cable was 15,457 lb and the range is from 11,836 lb to 18,975 lb. Since it is desired to have less cable and strut material volume, the final topology has very few elements.

Table 1: Leading Edge Nodal Deflections for HECS wing

	Span Change (as % original Span)	Thickness Change (as % original thickness)	Chord Change (as % chord length)
LE (obtained)	0.05%	5%	0.11%
LE (desired)	0.04%	5.3%	0%

3.1.2 TSCh wing

The next set of results are for two bays of NextGen's TSCh wing. The final topology consisted of 2 cables, 25 struts and 25 voids.
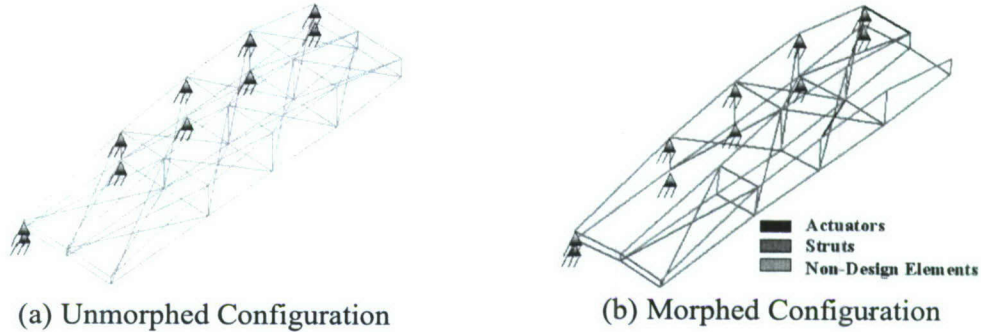

(a) Unmorphed Configuration   (b) Morphed Configuration

Figure 5: TSCh Wing – Optimal Topology

The topologies for the initial ground structure in the un-morphed configuration and that of the morphed configuration are shown in Figure 5. The obtained leading edge nodal deflections and their desired values are given in Table 2 for the leading edge node of the first bay. The average actuation force per cable was 15,405 lb and the range is from 16,587 lb to 19,252 lb.

Table 2: Leading Edge Nodal Deflections for TSCh Wing

	Span Change (as % original span)	Chord change (as % original chord)	Thickness change (as % original thickness)
LE (obtained)	12.6%	3.3%	25%
LE (desired)	26.4%	11.3%	0%

3.1.3 TSCh wing working model

In another approach, cells with pre-defined topology such as a parallelogram linkage mechanism were used. The amount of morphing depends on the arrangement of the cells and the cell sizing. This approach was used to design a morphing mechanism for TSCh wing. The cross-section of these links is assumed to be square and the size is determined using a strength-based approach. As the gross weight of the aircraft increases, the required weight of the morphing mechanism also increases. For a 400 lb. aircraft, the weight fraction becomes approximately 10%. An aluminum prototype was developed to demonstrate cellular mechanisms for planar morphing (Figure 6). The actuation is accomplished by winding a single cable around a spool connected to a small motor. The desired morphing performance is achieved successfully. A 55 % span change and 44° sweep are obtained when a 61% span change and 43.3° sweep are desired.
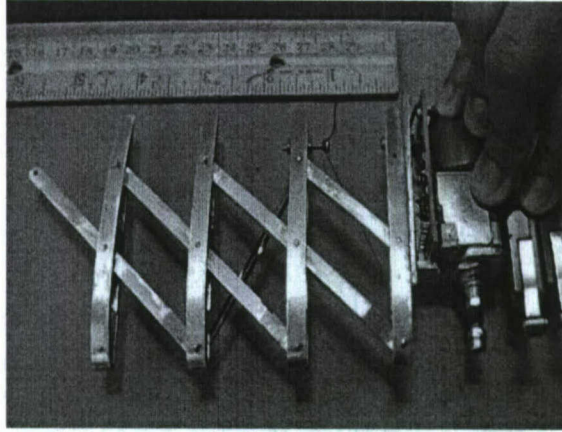
Figure 6: Prototype of cellular mechanism for TSCh wing

3.2 Compliant 2-D cell

The unit cell in this approach, shown in Figure 7, has four sides, each consisting of a stiff section with flexures at the ends. Each cell is fabricated from a single material such that there are no discontinuous connections between the flexures and stiff sections. For larger sized aircraft the benefits of using different materials for the separate sections of the unit cell were also considered [17].
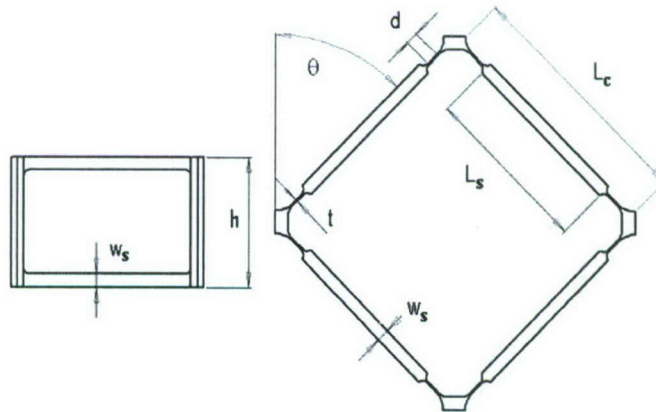

Figure 7: Unit Cell Base Design

The structure was designed to be contained within a specified percentage of the chord and thickness of the wing. This requirement defines the maximum height (h) and width (c_{str}) of the structure. The side length (L_c) of each cell is a function of this width, the cell angle (θ), and the number of rows of cells in the chord direction (NR). Dimensions of the cells were chosen such that each cell is able to support the local aerodynamic loading while the structure is fully deformed. Failure is assumed to occur when the stress experienced by the cells at the ultimate loads exceed the yield stress or critical bucking stresses. The cells are uniform in the chord direction but vary along the span.

An RC-sized aircraft was used as a starting point for the design. The RC aircraft had a gross weight of one pound, a span of 35 in., and a planform area of 350 in². A load factor of 3 and a

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factor of safety of 1.25 were used to determine the maximum loads that the aircraft will experience. This small aircraft was chosen since its size is ideal for future test models. Dimensional scaling based on the RC aircraft's geometry was used to compare the performance of the structure at different gross weights.

Figure 8 (left) shows the effects of scale and number of cell rows on the performance and structural weight of the aircraft. As shown in the figure, as the gross weight of the aircraft increases, there is a subsequent decrease in the maximum change in span that can be achieved. To offset this effect, the number of cell rows between the leading and trailing edges can be increased. As the gross weight of the aircraft increases, the root portion of the wing gradually becomes non-morphing, resulting in an overall decrease in performance. Also shown in the figure is the estimated structural weight penalty associated with morphing for this structure. This penalty can be quantified as the difference between the structural weight of the morphing structure and a passive structure that can carry the same aerodynamics loads.
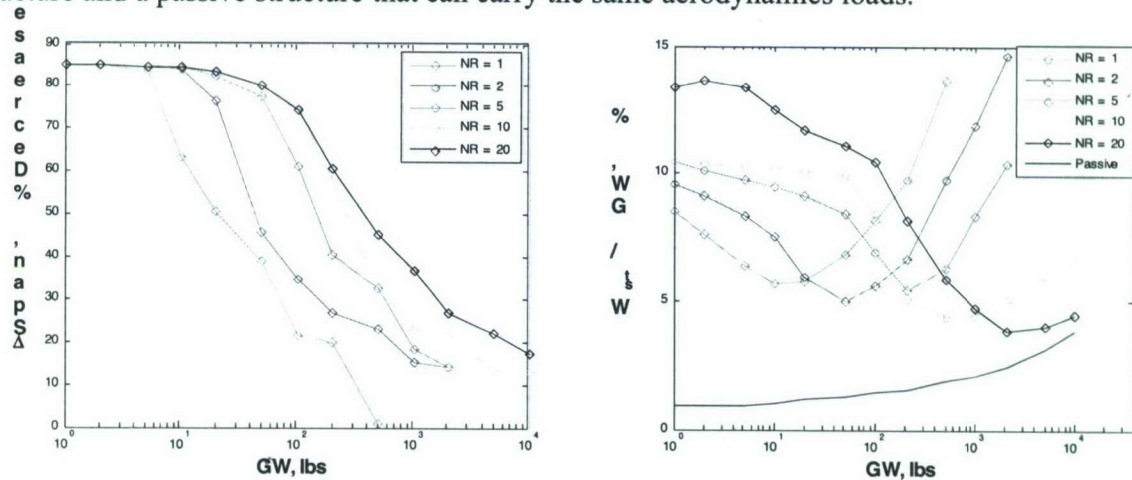

Figure 8: Scaling effects on morphing wing performance and structural weight

The number of cell rows in the morphing wing affects the structural weight fraction and, to a lesser extent, the change in span. Figure 8 (right) shows the effect of increasing the number of cell rows on the weight fraction of the morphing wing structure. Increasing the number of cell rows increases the total number of cells, but reduces their size. The geometry of the cells remains the same, however, and, since the cells are smaller, the lengths of the stiff sections decrease. Since the width of the stiff section is driven by its critical buckling load, the reduction in length of the stiff section decreases the width needed to ensure that buckling does not occur. This results in a decrease in the weight fraction of the structure. The number of cell rows is limited by the ability to fabricate small cells.

A non-linear FEA was used to determine the required actuation loads. Frame elements were used to model each cell, using one element for each flexure and stiff section. At one corner of the cell, the joint was fixed. At the opposite corner, the cell was given a nodal displacement corresponding to predetermined change in span. The resulting reaction force is the load required to deform the structure. The necessary cell actuation load decreases with distance from the fuselage. Since the cells in one row are connected in series, the maximum actuation load is the

sum of the forces needed to completely deform the parallel cells located at the root of the structure. The maximum actuation force is on the order of 3-5 times the gross weight.

Figure 9 shows the actuator mass and mass fraction as functions of the gross weight of the vehicle. Two possibilities were considered for the actuation. The first uses a single actuator, whereas the second uses a series of parallel actuators, one for each cell row. For a 10 lb aircraft, the weight fraction for a single actuator designed to deform the entire structure is 2.30%. If parallel actuation is used, the actuator weight fraction is 0.53%. At a gross weight of 50 lbs the actuator weight fraction for single and parallel actuators are 5.72% and 1.31%, respectively. This indicates that a single actuator is perhaps impractical for the 50 lb aircraft due to the larger weight penalty. Parallel actuation, however, is feasible based on the smaller weight penalty.
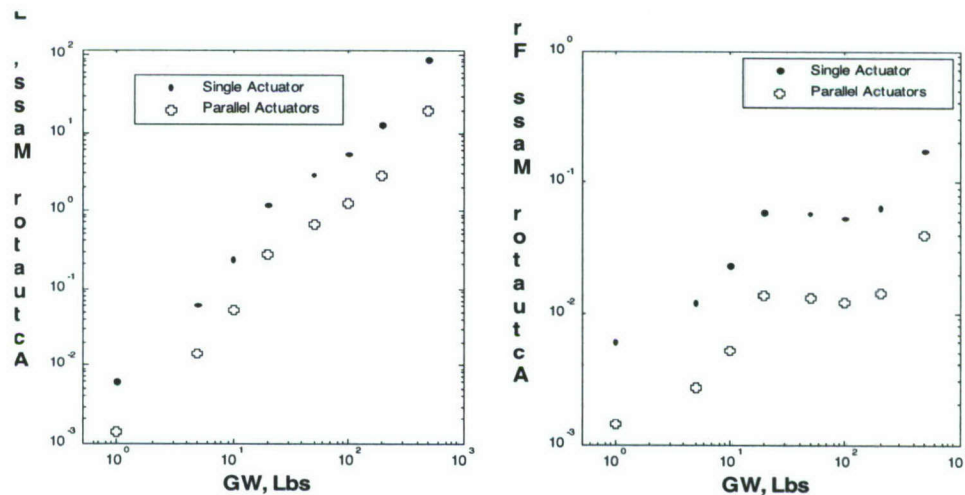

**Figure 9: a) Actuator mass as a function of gross weight.
b) Actuator weight fraction as a function of gross weight.**

The internal structure for a one pound RC-sized aircraft wing was designed and built for evaluation purposes. Figure 10 shows the internal structure in the fully extended configuration.
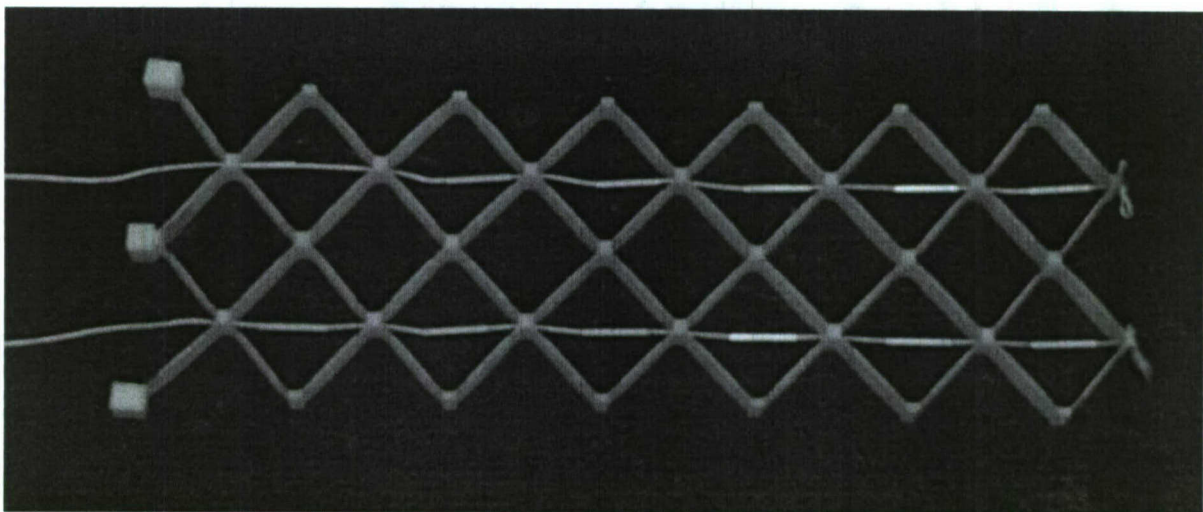

Figure 10: Prototype using 2-D morphing structures

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3.3 Flexible skin design

A unit cell for the cellular structure of a morphing skin is shown in Figure 11. Results were first obtained for an aluminum cellular core. Sample variations in E_1 (effective Young's modulus of the cell in horizontal direction) of the core, as a function of cell angle, θ, for various values of α ($= h/l$) (and $\beta = t/l = 0.12$) are shown in Figure 12. The extensional stiffness of the core is substantially lower than that of a homogeneous skin of the same mass. Figure 13 shows the maximum global strains of the core in the y- and the x-directions, versus cell angle, θ, due to loading in the y-direction. Maximum global strains correspond to local strains reaching their failure limit of 0.36%. For negative θ (auxetic cores), the maximum global strains in the y-direction exceed 4%. If the wall thickness is reduced by half (to 0.05), the maximum global strains are as high as 8% for an aluminum core. For a 30 deg "isotropic" honeycomb core of 1 cm depth, the extensional stiffness is 2% of that of a 1 mm thick isotropic aluminum sheet skin of the same mass, while the bending stiffness is increased 25 times. For a -30 deg cell, A_{11} is about 6%, A_{22} is < 1%, and the bending stiffness is ~8 times. For a 60 deg cell, A_{11} is about 0.3%, A_{22} is about 12%, and the bending stiffness is ~33 times.
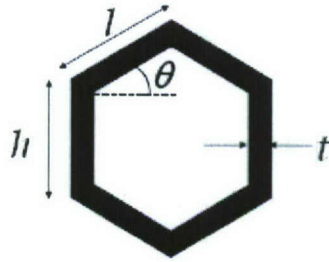

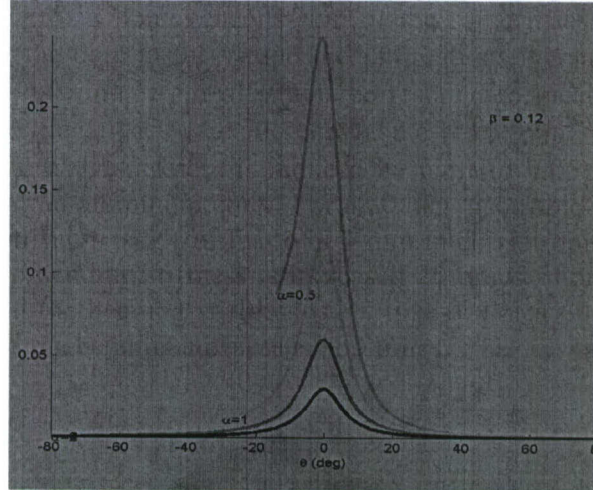**Figure 11: A unit cell for cellular skin with nomenclature**

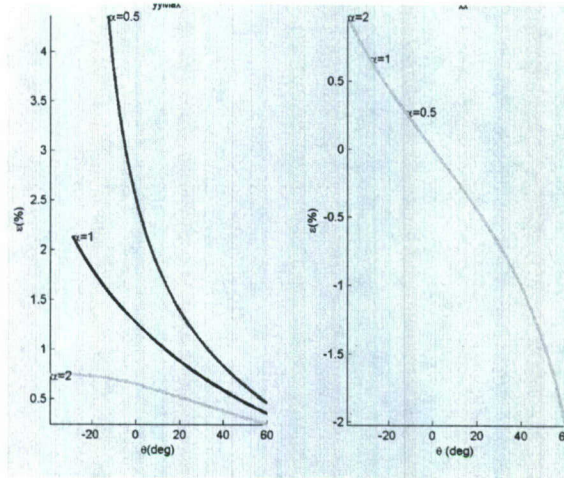**Figure 12: E_1 versus θ (for different α)**

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Figure 13: Core max. strains, versus θ

Next, a softer (E = 3 GPa), higher-strain capable material was considered. As the core is loaded, it undergoes large deformations prior to failure (see Figure 14). Since the individual cells change shape considerably, nonlinear ANSYS analysis was used. Figure 15 shows the sample variation in local deformation versus global deformation for a -30 deg cellular core. If the local strain-to-failure is assumed to be about 7%, global strains can be as high as 36%, without core failure. With even higher strain-capable materials (a hard plastic like Delrin that has strain-to-failure of up to 30%), the global strain capability of the skin could increase substantially. Further results and discussion can be found in [18].
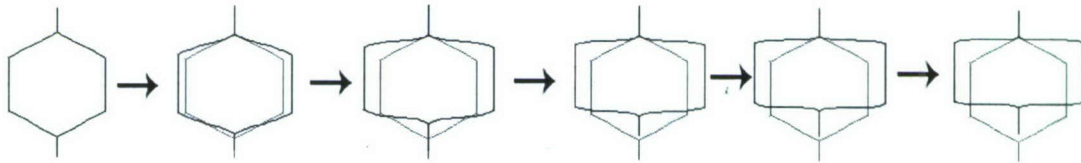

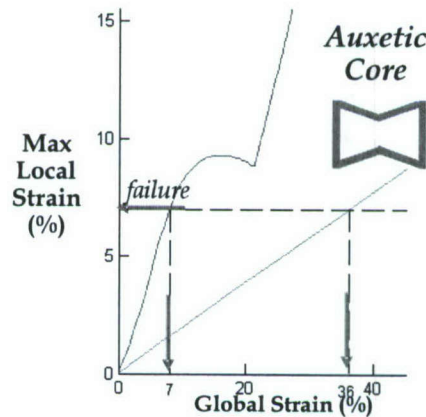**Figure 14: cells of a softer material core undergoing large deformations under loading**

Figure 15: Local Strains versus global strains for increasing loading levels
(red for loading in y, blue for loading in x)

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A contact-aided compliant mechanism was also designed to alleviate stresses and stiffen the structure in the transverse direction so that the morphing performance can be improved. The design consists of a compliant cell (with positive or negative Poisson's ratio) with an internal mechanism similar to a piston-cylinder connected to two collinear internal arms of the cell, as shown in Figure 16. The figure shows a unit cell with the contact-mechanism. When the mechanism is sufficiently deformed, contact takes place and the contact members, previously not under direct loading, become structurally loaded. Depending on the circumstances, this reduces either the stress of the overall mechanism, or the out-of-plane deformation under aero loads. Figure 17 demonstrates the use of contact for stress-relief. It shows that as the global strain increases initially, the stress increases, but following contact, the maximum stress is reduced.
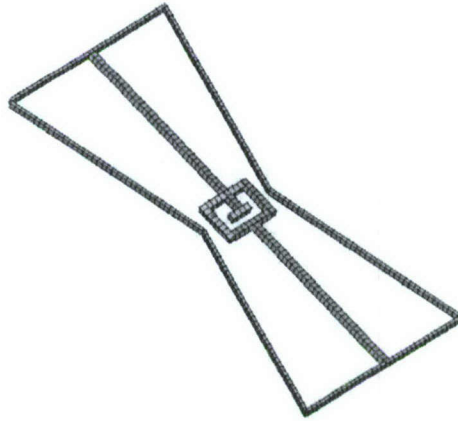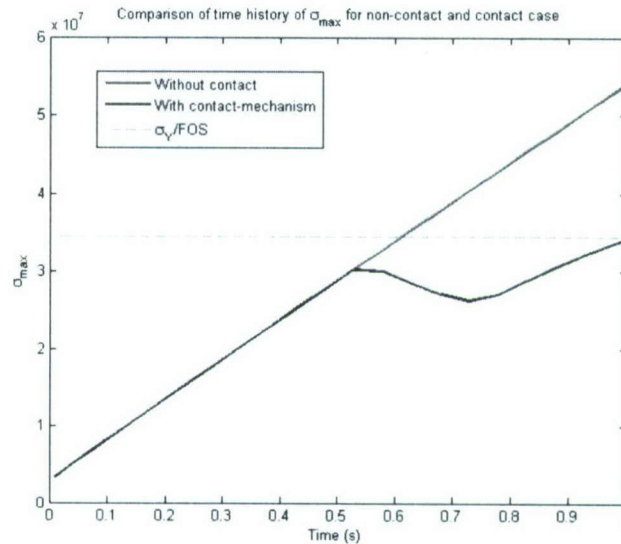
Figure 16: Geometry of contact-aided compliant cell

Figure 17: Demonstration of stress-relief using contact

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A 1 lb. RC aircraft was considered for the initial analysis of aerodynamic loading on the morphing skin. The half-span of the wing is divided into a number of honeycomb cells. The aerodynamic loads are applied at a specified number of points at which the skin is connected to the underlying morphing structure. The rectangular portion of the skin between four adjacent connection points defines a skin element. The skin thickness is then determined as needed to restrict the maximum out-of-plane deformation below a threshold value. The contact mechanism is designed so that the maximum stresses in the honeycomb core remain below the allowable stresses, or so that the maximum out-of-plane deformation is reduced. This procedure is repeated for different combinations of the number of skin elements and the number of cells per element.

Figure 18 shows a typical result for stress-relief. If contact is used to restrict the out-of-plane deflection, the resulting skin design is thinner and lighter. A brief set of result for combinations of number of skin-elements and number of cells per unit skin-element is shown in Figure 19. For more comprehensive results, see [19].
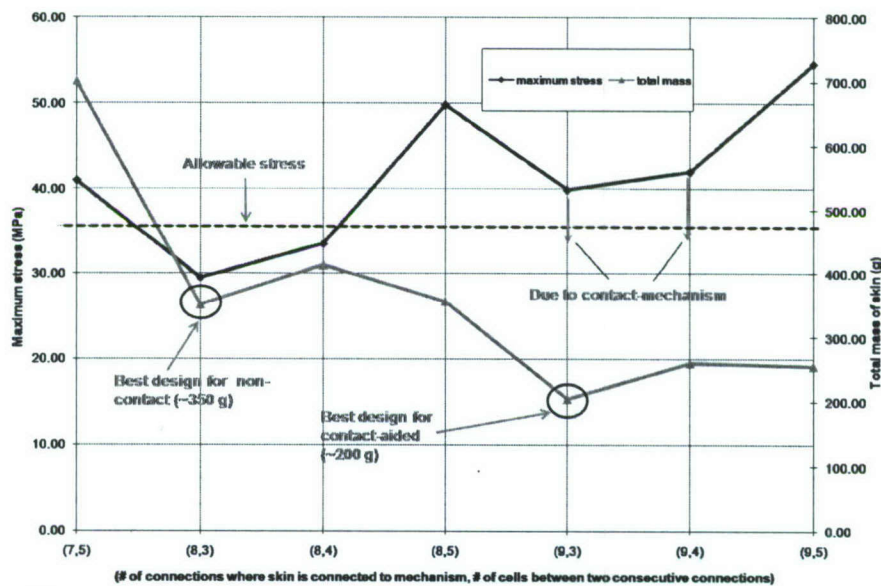

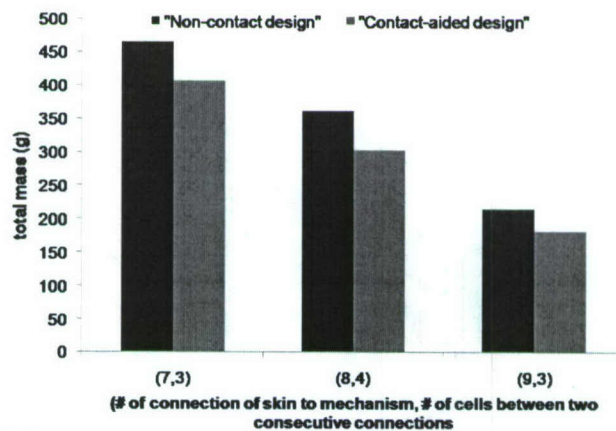**Figure 18: Variation of maximum stress and total skin mass for different connections**

Figure 19: Total mass for contact-aided and non-contact skins for different connections

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4. Conclusions

Aircraft structures have evolved for over a century to become very light, strong, and stiff. Their stiffness and strength rely, to a large extent, on a load-bearing skin. Morphing structures provide the possibility of large-scale, reconfiguration of a wing structure, enabling greater efficiency for each flight condition. Although structural and actuator weight necessarily increase with morphing capability, overall performance gains can offset these with fuel savings or by enabling new aircraft missions. Large-scale reconfiguration of the structure causes the drag and power curves of the aircraft to be shifted enabling efficient flight over a wider range of airspeeds. This potentially increases the difference between minimum loiter speed (for maximum time on station) and dash speed (at minimum drag).

The structural concept addressed in this research employs an articulated internal structure (a tendon-actuated compliant frame) and a relatively soft skin. A parallel genetic algorithm was developed for the optimal design of the topology of unit cells in a 3-D articulated structure. A six-noded octahedral unit cell with diagonal tendon actuation was obtained. A finite element analysis was subsequently performed on a wing made of these unit cells and sized for a representative vehicle weighing 3000 lbs (1360 kg). The weight of the truss wing (without the skin and actuators) was comparable to that of conventional stiffened skin construction although its deflections are larger.

A 3-D cellular truss structure, however, can be fairly complex with a large number of cables per unit cell, and the wing area change possible using these structures is limited. If actuation involves working against the lift forces or if the actuators are in the load path, then the gross weight of the aircraft might be limited to something in the range of a few hundreds to thousands of pounds. And even in-plane actuation may involve high forces in the tendons, resulting in high actuator weight. This could be addressed by employing morphing only in key locations, or by using beams to carry the lift loads so that the actuating cables act only against the lower in-plane loads. This motivates the consideration of 2-D structures.

A 2-D cellular morphing wing concept developed is capable of achieving large changes in wing span, aspect ratio, and planform area. A 1-lb RC aircraft was used as the starting point for the design. At this scale, the wing structure was predicted to be capable of an 85% decrease in the span with a structural and actuation weight of 3.2% of the gross weight. The morphing capability of this aircraft structure was verified using a prototype of the structure.

Dimensional scaling was used to compare designs having gross weights between 1 lb and 10,000 lbs. As the gross weight of the aircraft increases, the achievable span reduction decreases. This is accompanied by increasing structural and actuation weight fractions. A system of parallel actuators was found to have a significant weight advantage over a single actuator, however, especially at higher gross weights.

The size and topology of an alternate 2-D structural concepts were determined using a genetic algorithm-based scheme. The design methodology was applied to two candidate morphing wing

structures and the results were found to be very promising. A parallelogram-based mechanism concept was designed, built, and tested, demonstrating the suitability of the design methodology.

The details of the compliant joints and the skin are critical to the success of these morphing concepts. The joints must be stiff axially and soft in bending, while the skin must have low membrane stiffness and higher flexural stiffness. Compliant joints that use pseudo-elastic SMA show promise, with some limitations likely at large scales (and loads).

A composite skin was investigated for its ability to meet the requirements of low-force actuation, while carrying lateral aerodynamic loads without excessive deflection. Skins with cellular cores and flexible faces sheets show promise. Contact-aided cellular cores offer additional potential benefits, including stress-relief and increased lateral stiffness.

While the benefits of morphing increase with aircraft gross weight, structural morphing capability decreases with gross weight. This suggests, for a given structural paradigm, there is a gross weight, on the order of several thousand pounds, at which continuous, smooth morphing is most advantageous and practical.

This investigation into smoothly morphing aircraft structures has yielded great insight into the problem, design procedures, and powerful design tools. Continued research is needed to address the many challenges that remain before smoothly morphing aircraft become practical.

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5. Mehta, Vipul, "Contact-aided compliant mechanisms for morphing aircraft skin," Ph. D. Dissertation, In progress, The Pennsylvania State University

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